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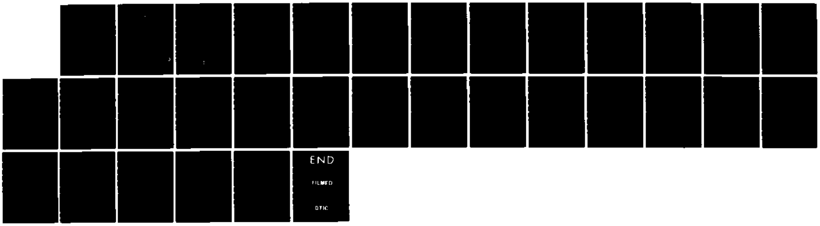

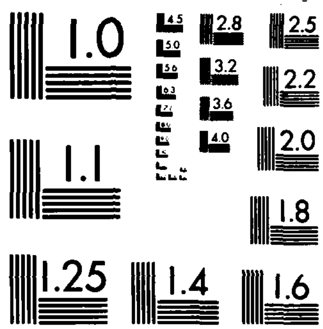

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MELBOURNE, VICTORIA

Aero Propulsion Technical Memorandum 422

PROPOSAL FOR MODIFICATIONS TO THE WESSEX HELICOPTER MAIN ROTOR GEARBOX VIBRATION MONITORING PROGRAM

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Approved for Public Release

COPY No JANUARY 1985

AR-003-985

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SUMMARY

Modifications to the RAN Recorded Tape Vibration Analysis Program for the condition monitoring of the main rotor gearbox in the Wessex helicopter are proposed to take advantage of recent developments in the techniques of signal averaging and computer enhancement of vibration data.

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CONTENTS

A 1

1. INTRODUCTION

In 1977, when the RAN Recorded Tape Vibration Analysis Program for the condition monitoring of the main rotor gearboxes in Wessex and Sea King helicopters was first introduced, it was envisaged that vibration analysis would be capable of detecting failures in gears and bearings alike on an equal footing with the already accepted techniques of oil-borne debris analysis. Since that time vibration analysis has been involved on at least three occasions with unusual vibration phenomena in Sea King gearboxes which can be directly correlated with the gearbox condition. Hence it would appear that vibration analysis does have a contribution to make to the monitoring of helicopter gearboxes, although earlier expectations of its abilities may have been rather higher than can readily be achieved in day-to-day use. The present view of gearbox monitoring in the UK [1] is that oil-borne debris analysis is still the most effective technique for detecting gear or bearing failures in which metallic debris is generated, but that vibration analysis has an indispensable role in the detection of fatigue cracks in gears. In this latter mode of failure, oil-borne debris analysis will probably never be effective due to the very small amounts of metal, if any, which are released during crack propagation.

However, the catastrophic fatigue failure in December 1983 of the input bevel pinion of Wessex main rotor gearbox WAK143 indicates that the technique of vibration spectrum analysis currently practiced by the RAN is simply not able to provide reliable and early detection of this type of failure. Fortunately, recent research [2-5] using the tape recordings of the vibration of WAK143 made prior to failure now make it possible to detect this type of crack more than 100 hours before failure by an alternative technique of vibration analysis called signal averaging. This technical memorandum reviews briefly these developments in vibration analysis and proposes modifications to the Wessex vibration monitoring program to take advantage of the improved capabilities offered by signal averaging. Equipment requirements are outlined and estimates of costs provided.

2. REVIEW OF DEVELOPMENTS IN VIBRATION ANALYSIS

2.1 Limitations of Spectrum Analysis

A small crack in a gear will only affect the vibration produced by the adjacent teeth as they mesh once per revolution of the gear. Because the duration of the event is short, the result in the frequency domain will be families of modulation sidebands about the meshing frequency and its harmonics, extending over a wide frequency range but at a low amplitude level, as illustrated in Figure 1 [6]. But normal gears can also show modulation sidebands due to inherent transmission errors between the teeth of the gears. Consequently, the detection of the modulation sidebands caused by a fatigue crack against the background of sidebands due to transmission errors and the normal background noise of a complex gearbox can be extremely difficult. The problem is compounded by the application of a weighting function to the original data to overcome the restriction imposed by the discrete Fourier transform that the data should be periodic within the time window [7]. Weighting functions cause discrete spectral components to broaden, making their separation more difficult, and introduce sidelobes which raise the level of the background signal.

Furthermore, the amplitude spectrum contains only half of the total information required to define a signal, with the remainder being carried in the phase spectrum. Thus it is conceptually possible for a normal gear and a cracked gear to have identical amplitude spectra. The phase spectra would of course differ, but even if the phase spectra were available, a simple visual inspection would be unlikely to help due to their greater complexity.

2.2 Introduction to Signal Averaging

One of the alternative methods of analyzing vibration is called signal averaging, also referred to as time averaging or synchronous averaging. Using a photoelectric or electromagnetic transducer, a pulse can be generated once per revolution of one of the shafts in a gearbox, as shown in Figure 2 [8]. With the aid of an instrument called a phase-locked frequency multiplier, which will be described in a later section, a signal can be produced which contains an exact integer number of pulses for each revolution of the shaft of interest, locked in phase with the rotation of that shaft. The signal from the vibration transducer can then be sampled and the first sample of each revolution averaged over many revolutions. Similarly, the second sample of each revolution is averaged, and so on, to produce the ensemble average for the complete revolution. If sufficient averages are taken, the ensemble average describes only the vibration generated by the gear or gears on the shaft of interest.

Signal averaging can also be viewed in the frequency domain as a process of comb filtering, in which the frequencies passed by the filter correspond to the teeth of a comb located at multiples of the shaft

rotation frequency. It can be shown that increasing the number of averages narrows the teeth of the comb, making the filter more effective [9]. For an infinite number of averages, the teeth of the comb become infinitesimally narrow, and although this can never be achieved in practice, it is commonly found that if the machine operates at a nearly constant speed then several hundred averages are sufficient. Because the signal average is periodic, the application of weighting functions is unnecessary. This eliminates the problems of sidelobes described earlier in the amplitude spectrum, and permits the easy and accurate digital filtering of the signal average by applying the filter characteristics directly to the frequency domain. For example, a signal average may be band-pass filtered by calculating the spectrum or Fourier transform of the signal average, setting the amplitudes of all components outside the passband to zero, and then calculating the inverse Fourier transform.

Signal averaging is not a new technique. It has been used extensively in the physical and biological sciences for many years, but its application to machinery vibration analysis is more recent [8]. It plays a key role in the very ambitious Mechanical Systems Diagnostic Analyzer proposed to meet NGAST 6638 in the UK [10], and in vibration monitoring equipment being developed by WHL [11]. As might be expected, the additional diagnostic power of signal averaging is only obtained at a price. Whereas conventional spectral analysis requires only the vibration signal which is to be analyzed, signal averaging requires in addition an accurate sampling signal locked in phase with the rotation of the gear of interest. As mentioned earlier, it is rarely possible to attach a speed-sensing transducer directly to the shaft of interest, necessitating the use of any shaft that may be accessible. The required sampling signal must then be obtained by phase-locked frequency multiplication.

2.3 Phase-Locked Frequency Multiplication

Figure 3 shows the elements of a digital phase-locked frequency multiplier. An input pulse train and the output of the divider M enter a phase detector which determines the phase difference between the leading edges of the incoming pulse trains and produces an error signal consisting of positive or negative pulses whose width is proportional to the magnitude of the phase error. The error signal is then smoothed by a low-pass filter to produce a steady voltage signal which drives a voltage-controlled oscillator (VCO). The output of the VCO passes to a divider D which generates the output signal and also to the divider M. If the phase of the input signal advances slightly ahead of the output of divider M, a positive error signal is generated which increases the frequency of the VCO so that the output of the divider M follows the change in phase of the input signal. The reverse happens when the input signal retards slightly. In this manner the system is able to track phase and frequency changes in the input signal. The ability of the system to capture and follow the input signal successfully is determined by the characteristics of the low-pass filter, the gain of the VCO, the factor M, and the rapidity with which the phase of the input signal changes. Note that because the output of the VCO is divided in frequency by M before passing to the phase detector, the loop will tend to stabilize at a VCO frequency which is M times the input frequency.

The output frequency, obtained by dividing the VCO frequency by D, is therefore given by M/D times the input frequency. By selecting appropriate values of M and D, a suitable sampling signal at an exact multiple of the rotation frequency of the gear of interest can be produced. Commercial frequency multiplier instruments using a single loop, such as the Spectral Dynamics SD134A Tracking Ratio Tuner, are available. Some of the signal averages presented in a later section were produced using an SD134A.

Because of the frequent appearance of prime numbers of teeth on gears, it is quite common for large values of M and D to be required. The problem is accentuated by the desirability of achieving a number of samples per revolution of the shaft of interest which is a power of two, in order to take advantage of the greater processing speed of the radix-two fast Fourier transform [7] in any subsequent processing of the signal average. In practice, there is a limit to the largest value of M which can be used, due to the increase in the time to acquire lock and the reduction in the loop gain and hence the ability to track with increasing M. Consequently it may be advantageous to use several loops in series to achieve the same M/D ratio. For example, if one phase of the Wessex gearbox alternator output is taken as a speed signal, it can be shown from the numbers of teeth on the appropriate gears that a sampling frequency f_s giving 256 samples per revolution of the input bevel pinion can be obtained from the alternator signal f_a by a four-stage frequency multiplier using the following ratios:

$$f_s = (19/61) \times (21/61) \times (16) \times (16) f_a \qquad (1)$$

For each stage of the loop, the natural frequency and damping ratio of the low-pass filter must be determined using available equations [12] to provide good tracking ability consistent with sufficient immunity to the noise and jitter of the alternator signal. A prototype frequency multiplier using the above ratios has been designed and built at ARL and used to produce some of the signal averages presented in a later section.

2.4 Vibration of Input Bevel Pinion 42 Hours Before Failure

The last tape recording of gearbox WAK143 before failure was made on 11th October 1983 at 324.3 hours since overhaul, approximately 42 hours before failure. The output of the gearbox alternator, nominally 400 Hz, was recorded routinely on the tape but, as with a number of other recordings of that period, the voltage level was too high causing severe distortion and rendering the alternator signal useless. Fortunately it was found that by band-pass filtering the vibration signal at the second harmonic of the meshing frequency of the input bevel pinion, a clean signal was obtained which could serve as an input for the Spectral Dynamics SD134A frequency multiplier. With a multiplication factor of 128 and division by 11, 512 samples per revolution of the input bevel pinion were obtained.

Figure 4 shows the signal average calculated at a torque of 300. At the start of the trace the signal average shows a regular waveform at a frequency of 44 cycles per revolution, or 44 orders, corresponding to the second harmonic of the meshing frequency. At the centre of the

trace there is a large perturbation in the meshing pattern as the part of the gear affected by the crack goes through the meshing region, after which the trace returns slowly to the normal meshing pattern. Hence a clear indication of the crack can be seen in the signal average at 42 hours before failure.

2.5 Vibration of Input Bevel Pinion 103 Hours Before Failure

The second-last recording before failure was made on 1st July 1983 at 263.4 hours since overhaul, approximately 103 hours before failure. The signal average, calculated using the band-pass filtered vibration signal to trigger the SD134A frequency multiplier, is shown in Figure 5. The dominant component of the signal average is at 44 orders, and while there are some minor amplitude variations, there is no large perturbation of the form observed at 42 hours before failure. Hence there is no clear indication of the crack by unaided visual inspection of the signal average at 103 hours before failure.

2.6 Enhancement of the Signal Average

A major difficulty in the visual detection of small abnormalities in the signal average is that it is hard to distinguish the small change in the vibration due to the abnormality against the large vibration pattern produced by the normal gear meshing. Over the years several techniques have been proposed to overcome this problem by enhancing the signal average. For example, it has been found empirically that by calculating the Fourier transform of the signal average, setting the amplitudes of the components at the meshing frequency and its harmonics to zero, and calculating the inverse transform, then the major contributions due to the normal gear meshing can be eliminated [8]. The signal which remains should therefore be representative of the departures from normal of the vibration, and in some cases it is found that this technique can enhance the effects of damage. Unfortunately this technique lacks a sound theoretical basis for application to gear problems, as the signal which remains after enhancement cannot be simply related to any measurable properties of the gear.

Recently it has been shown that by band-pass filtering the signal average about one of the largest meshing harmonics, eliminating the harmonic itself, and calculating the envelope of the remaining signal, a function is obtained which is closely related to the amplitude and phase modulation present in the original signal average. If a(t) and p(t) represent the amplitude and phase modulation respectively, then the envelope e(t), for a(t) and p(t) small, is approximately given by [13]:

$$e(t) \propto \sqrt{a^2(t) + p^2(t)} \qquad (2)$$

Figure 6 shows the amplitude spectrum of the signal average at 103 hours before failure. The major component in the spectrum is at 44 orders, the second harmonic of the meshing frequency, with an amplitude about 7 times that of the second largest component. By setting the

amplitudes of all spectral lines outside the frequency range 30 to 58 orders to zero, the signal average can be band-pass filtered. After setting the amplitude at 44 orders to zero, the envelope of the signal can be calculated using the Hilbert transform [14], giving the result shown in Figure 7. At the centre of the trace is a clear broad peak produced by the fatigue crack. As there was little amplitude modulation present in the original signal average shown in Figure 5, it would appear that the major contribution to the peak in Figure 7 is the phase modulation p(t). This is a particularly interesting result, because the effect of a crack on the vibration is usually viewed as an amplitude modulation of the original meshing vibration [6,8]. If this example is typical of such defects, then it may be possible to detect them earlier by the phase modulation they produce than by the amplitude modulation. Using a variation of the above technique, the estimate of the phase modulation shown in Figure 8 can be obtained. At the location of the crack there is a phase lag as the reduced stiffness of the gear causes it to deflect under the load. Because the calculation is based on the second harmonic of the meshing frequency at 44 orders, estimates of the actual phase lag in terms of shaft rotation may be obtained by dividing by 44.

2.7 Assessing the Signal Average

One of the greatest drawbacks of spectral analysis is the need to examine detailed vibration spectra containing many components. To a large extent, signal averaging can eliminate the problem as it is only necessary to search the enhanced signal averages for peaks of the type shown in Figure 7. More valuable would be a technique for quantifying the indications of damage which might be present in the enhanced signal average, preferably into a single number which can be used for a GO/NOGO assessment of the machine condition. Many such numbers have been proposed already for similar tasks, including the crest factor which is the ratio of the peak-to-peak level to the root-mean-square level, and the kurtosis which is the normalized fourth statistical moment.

The kurtosis K of a population x_i is given by:

$$K = [\sum (x_i - m)^4] / [N s^4] \qquad (3)$$

where N = number of samples
m = mean value
s = standard deviation

For a population with a normal (random) distribution, the kurtosis is 3. Because the kurtosis is calculated using the fourth power of the difference between a sample and the mean value of the population, it is sensitive to local, narrow peaks. This has already lead to its application in the vibration monitoring of rolling element bearings [15], and also makes it a suitable parameter for quantifying the enhanced signal average. Table 1 shows the kurtosis calculated after each stage of the enhancement of the signal average taken at 103 hours before failure. The kurtosis of the original signal average is very close to the value of 1.5 expected for a pure sinusoid. After enhancement, a kurtosis of 9.2 is obtained due to the strong peak shown in Figure 7.

2.8 Comparison with Other Gearboxes

Tables 2 and 3 show the values of kurtosis calculated for the enhanced signal averages of 15 other Wessex gearboxes prepared using the same procedure, except that when the largest component in the spectrum of the signal average is the fundamental meshing frequency at 22 orders, the band-pass filter has been set to pass 8 to 36 orders inclusive and the component at 22 orders has been eliminated. It can be seen from the tables that all the kurtosis values for the sound gearboxes fall in the range 1.9 to 3.3, with the majority between 2.0 and 3.0. There is a clear margin between the sound gearboxes, having values of kurtosis below 3.3, and gearbox WAK143 with a kurtosis of 9.2, even at 103 hours before failure.

2.9 Vibration of Input Bevel Pinion 233 Hours Before Failure

The third-last tape recording of gearbox WAK143 before failure was made on 7th March 1983 at 133.4 hours since overhaul, approximately 233 hours before failure. Applying the enhancement procedure to the signal average produced the kurtosis values shown in Table 4. All of the values are close to, if not greater than, the limit of 3.3 observed for the sound gearboxes. While the gearbox cannot be rejected outright on this basis it does appear likely that at some time between 233 hours and 103 hours before failure the kurtosis would have increased sufficiently to mark the box as defective.

3. PROPOSAL FOR MODIFICATIONS TO VIBRATION ANALYSIS PROGRAM

3.1 Need for New Equipment

The procedures for the calculation of the signal average, the enhancement of the signal average, and the calculation of the kurtosis cannot be performed on the Hewlett-Packard 3582A spectrum analyzers held by the RAN because these instruments have no facilities for the external control of sampling nor for programmed arithmetic calculations. Commercial instruments are available which will perform signal averaging but the need for arithmetic calculations can only be met by a programmable calculator or a computer. It would appear that the most cost-effective solution is to combine the operations of signal averaging, enhancement and kurtosis calculation under the control of a small computer. The equipment proposals in the following sections are based on this premise.

3.2 Recording of Vibration Data

It is proposed that the present procedures and equipment used for the inflight recording of the gearbox vibration remain essentially unchanged. Consideration has been given to the online assessment of the condition of the input bevel pinion and while it is theoretically possible, the ARL view remains that the practical difficulties of operating a small computer system in the high-vibration environment of a helicopter are best left until experience has been gained using ground-based analysis. Furthermore, tape recordings of vibration data have the very important advantage that they enable subsequent analysis by a variety of methods. The enhancement procedure described in a previous section could not have been developed without the recordings of WAK143 made prior to failure.

The signal from the alternator will be recorded as at present to provide a speed signal for the frequency multiplier. The configuration of the equipment for recording is shown in Figure 9a.

3.3 Analysis of Vibration Recordings

In the laboratory the tape recording will be replayed with the vibration signal going to a low-pass filter to prevent aliasing errors and then to the analogue input of an analogue-to-digital converter board in the computer. The alternator signal will be input to the multistage phase-locked frequency multiplier designed by ARL, the output of which will be connected to the external clock input of the analogue-to-digital converter. The configuration of the equipment for analysis is shown in Figure 9b. After the phase-locked frequency multiplier has locked onto the alternator signal, the signal average will be calculated by the computer, stored on disc, and the enhanced average calculated and its

kurtosis determined. A summary of the result will be produced on a small printer to provide a permanent record of the analysis.

At this stage it is expected that the analysis by signal averaging will be additional to the spectrum analysis currently performed. To maintain the workload at a similar level, ARL propose that the recording and analysis of some of the lower torque settings be discontinued. Should experience with signal averaging prove satisfactory during the next few years, the RAN may elect to discontinue spectrum analysis completely.

The move towards a small computer system may seem daunting when personnel with limited or no computer experience will be required to operate the equipment, but if the programs are carefully organized and written the system should require minimal training and be easier to operate than the present Hewlett-Packard spectrum analyzer. It is proposed that the computer should prompt the operator at each step of the process, and should perform whatever self-checks are possible to ensure that valid results are produced. ARL have considerable experience in the programming of small computers and will supply all the applications software required provided that the equipment purchased by the RAN is compatible with that used by ARL.

3.4 Compatibility with ARL Equipment

There are many makes of small computer system which could be considered for this task. ARL have considerable experience in the operation of Digital Equipment Corporation (DEC) PDP11 and LSI11 machines, and it is urged that any equipment purchased by the RAN be hardware and software compatible with that used by ARL. The selection of incompatible equipment will delay greatly the implementation of a monitoring program, hinder the transfer of data between the RAN and ARL, and rule out any ongoing software development. A list of the suggested purchases is given in Table 5 together with conservative estimates of the cost. The items shown constitute a small, fast computer well suited to the task proposed.

5 Future Developments

One of the great advantages of a computer-based system is that simple modifications and even major revisions of the analysis procedure can be readily incorporated by changes to the programs. If compatible equipment is purchased, all development can be performed at ARL and revised, ready-to-run systems sent to the RAN through the post on a flexible ("floppy") disc. Probably the first direction for further development would be the application of the techniques described here to the monitoring of other major gears in the Wessex and subsequently in the Sea King.

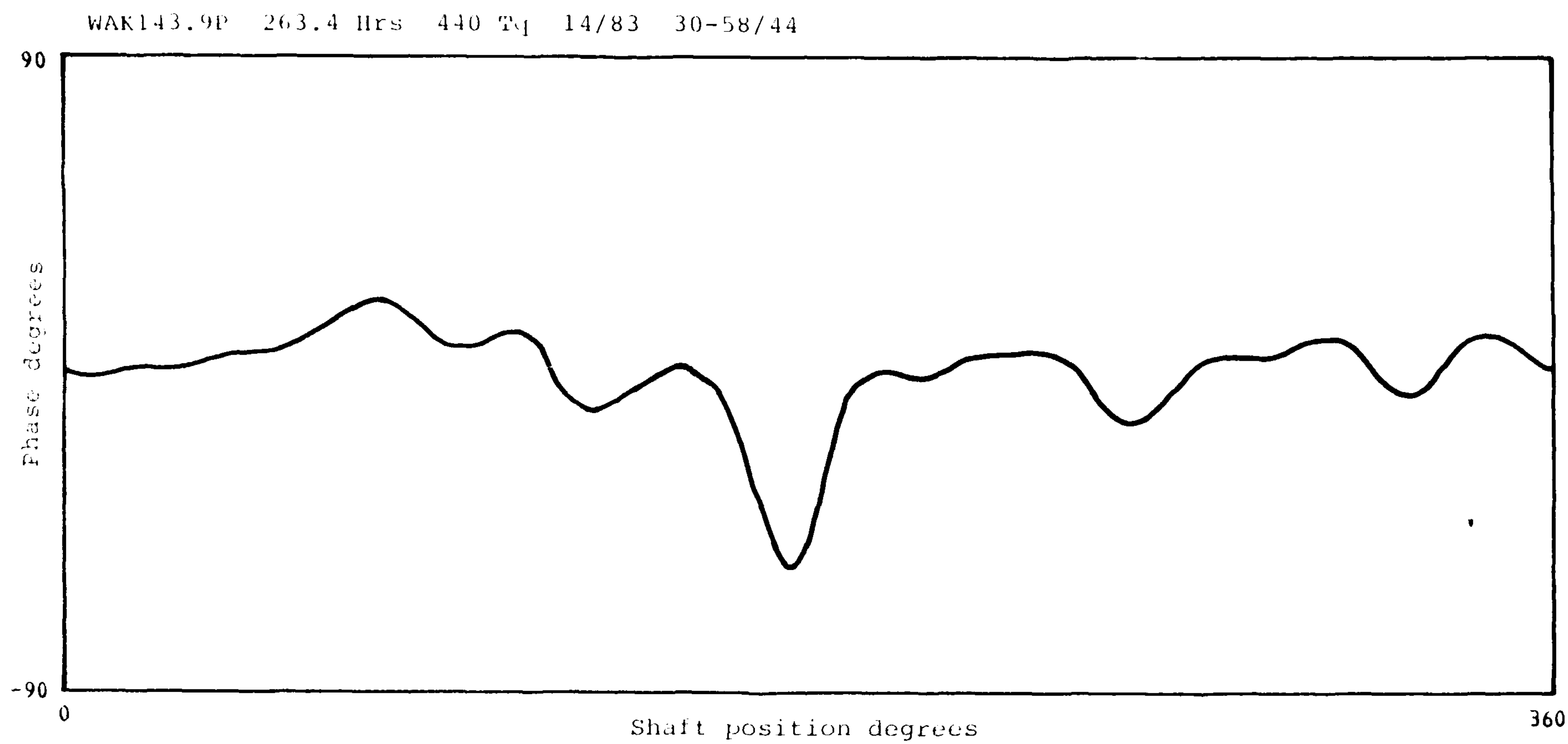

FIG. 8 PHASE OF SIGNAL AVERAGE OF GEARBOX WAK143 AT 263.4 HOURS

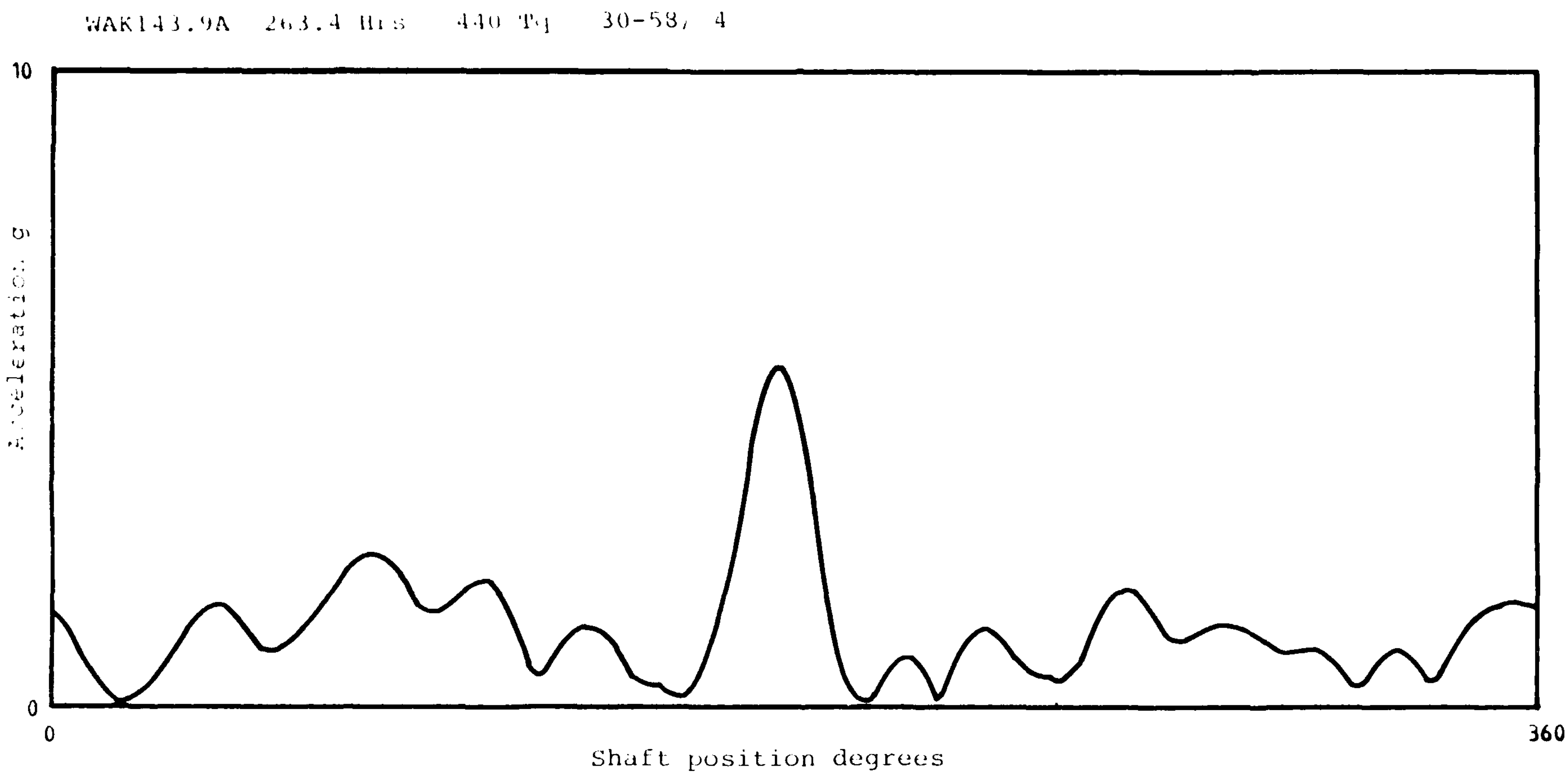

FIG. 7 ENHANCED SIGNAL AVERAGE OF GEARBOX WAK143 AT 263.4 HOURS

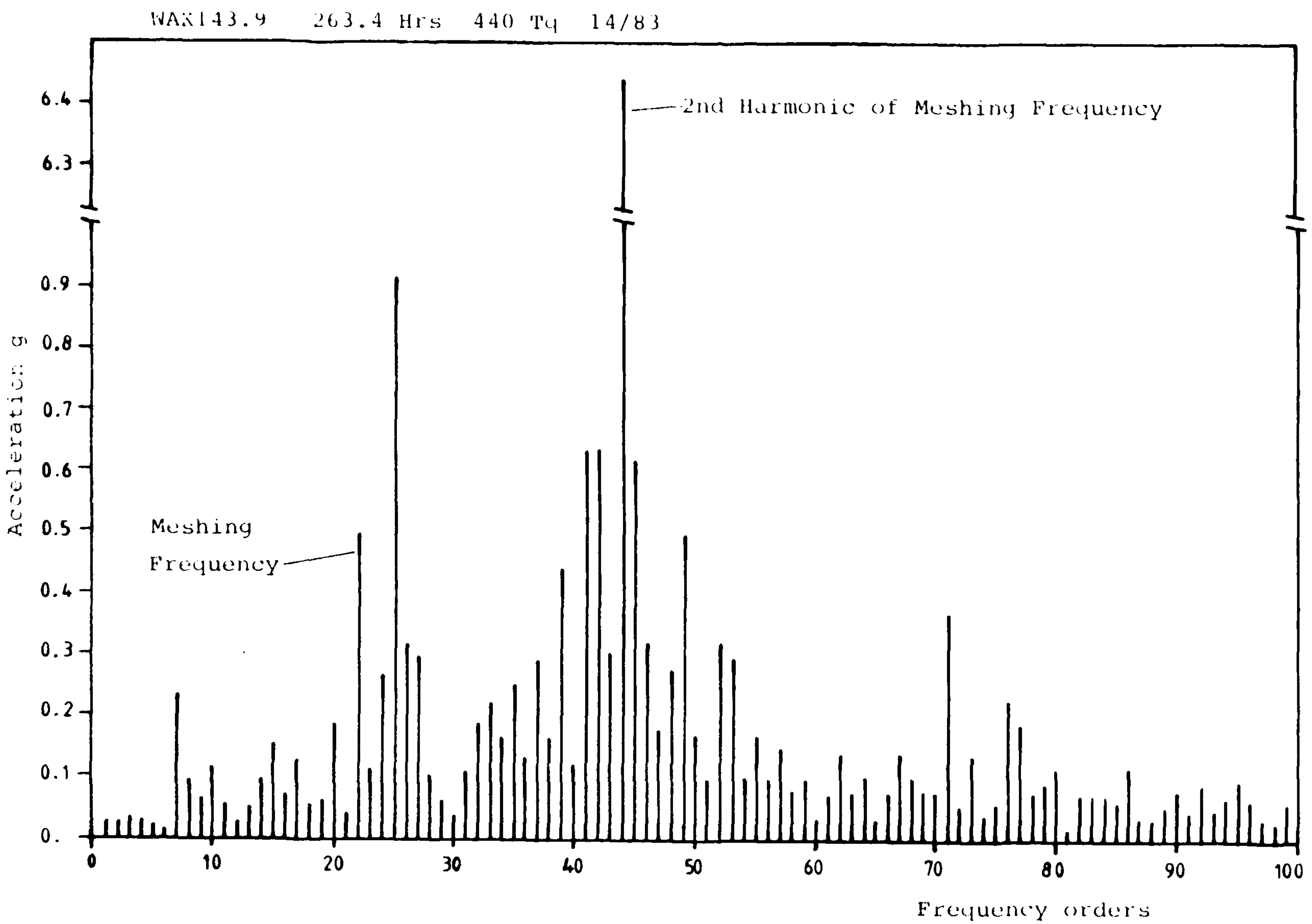

FIG. 6 SPECTRUM OF GEARBOX WAK143 AT 263.4 HOURS

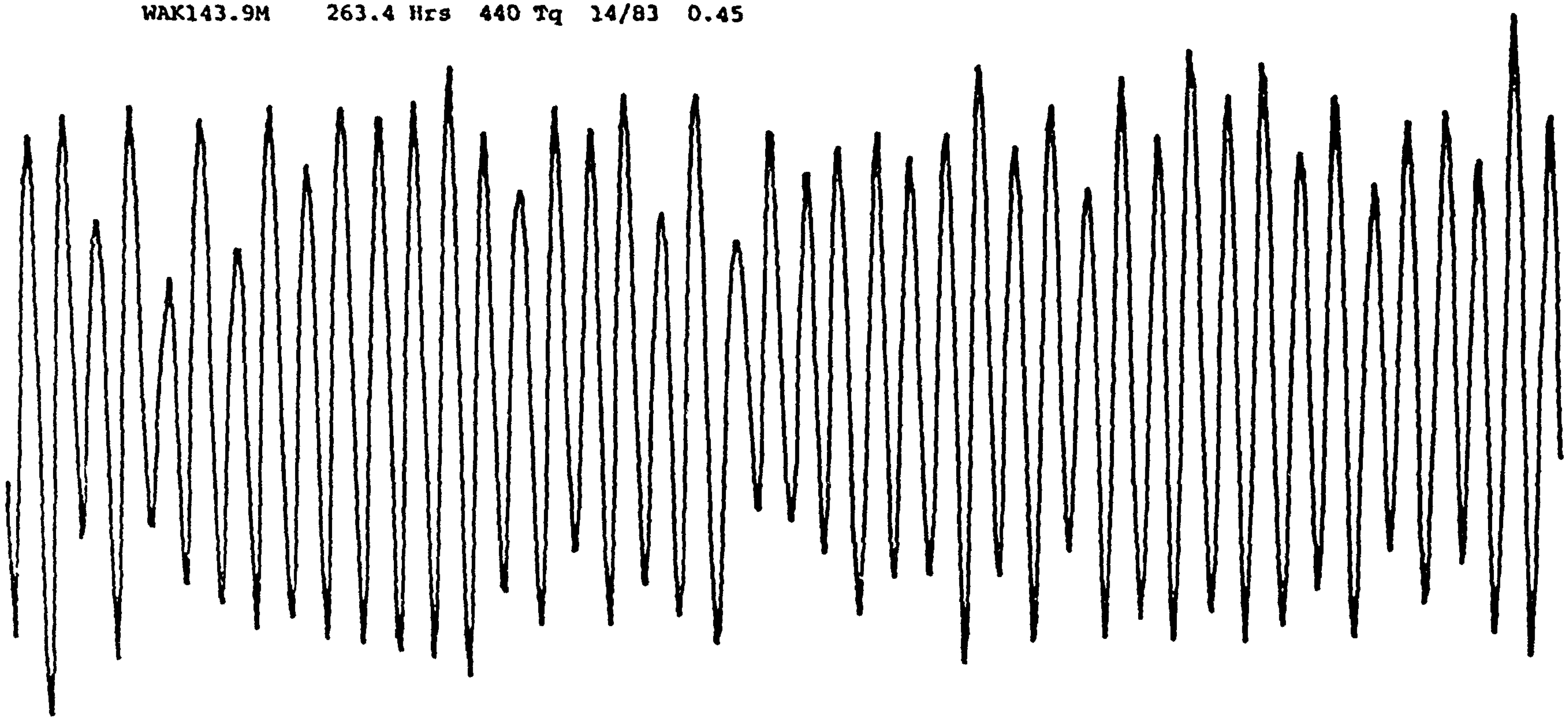

FIG. 5 SIGNAL AVERAGE OF GEARBOX WAK143 AT 263.4 HOURS

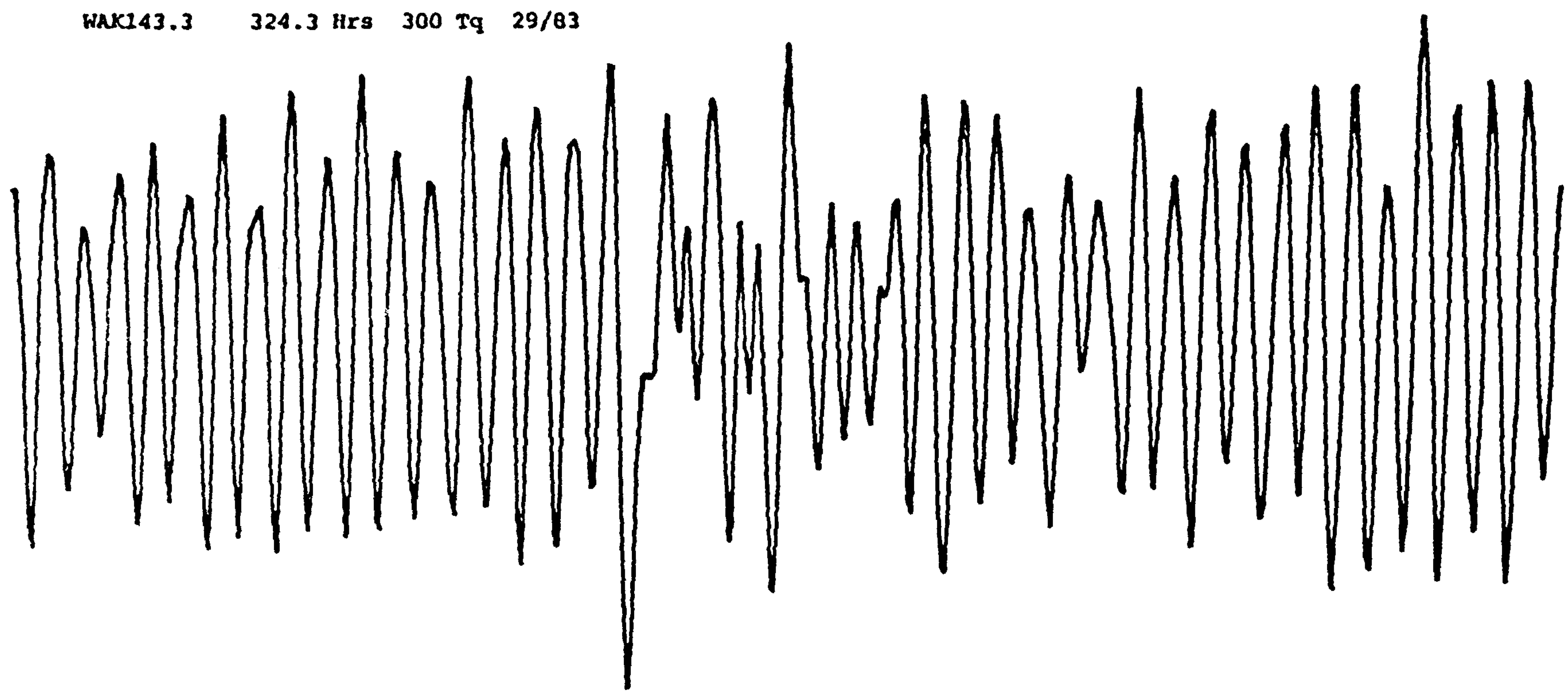

FIG. 4 SIGNAL AVERAGE OF GEARBOX WAK143 AT 324.3 HOURS

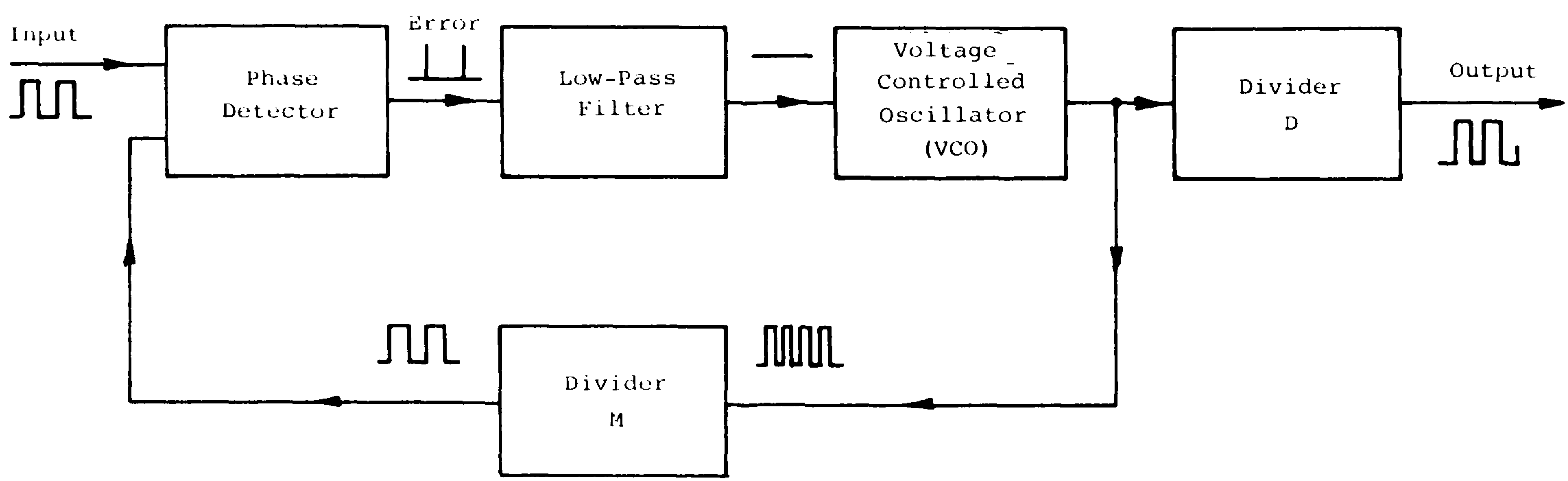

FIG. 3 PHASE-LOCKED FREQUENCY MULTIPLIER

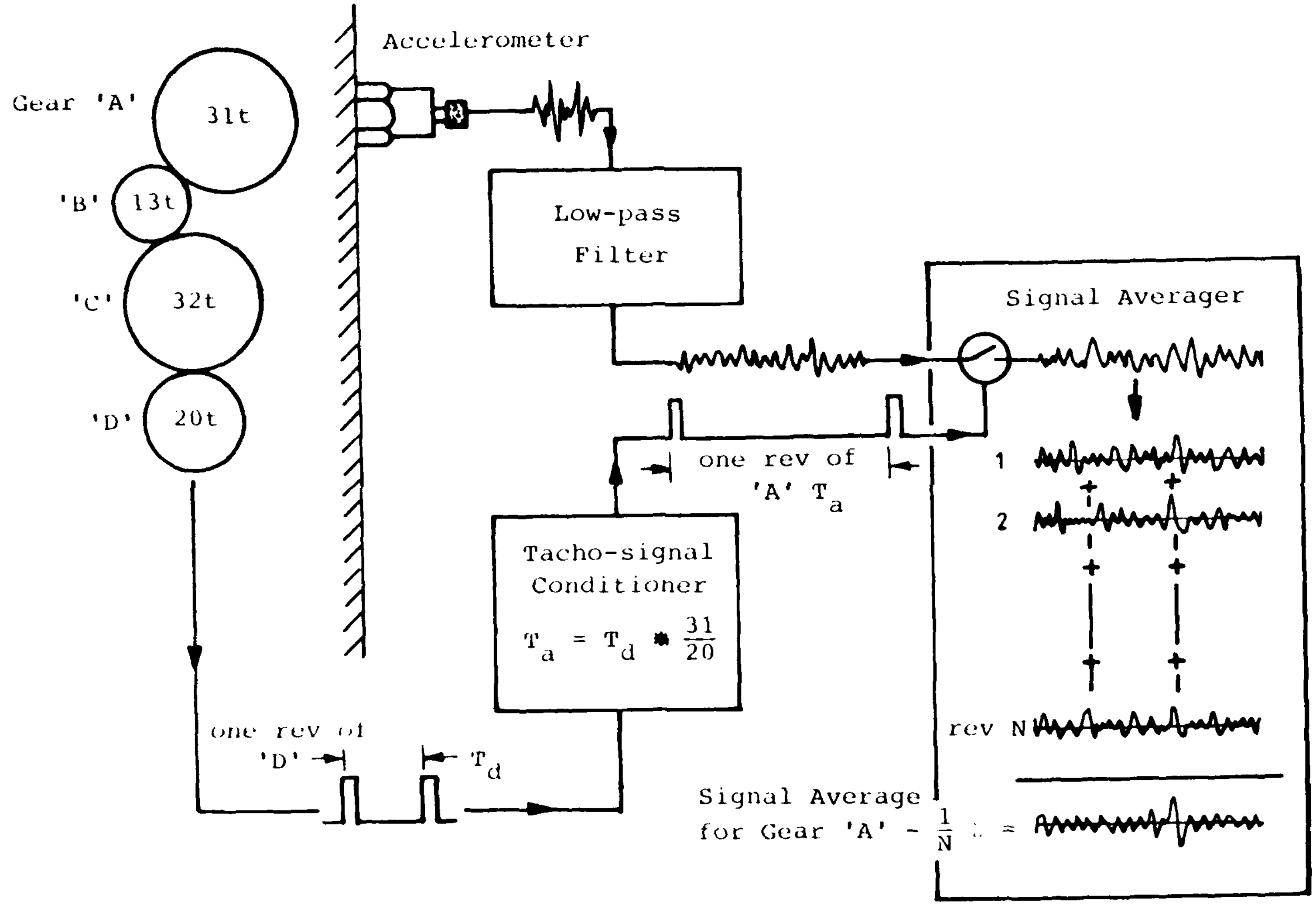

FIG. 2 PRINCIPLES OF SIGNAL AVERAGING

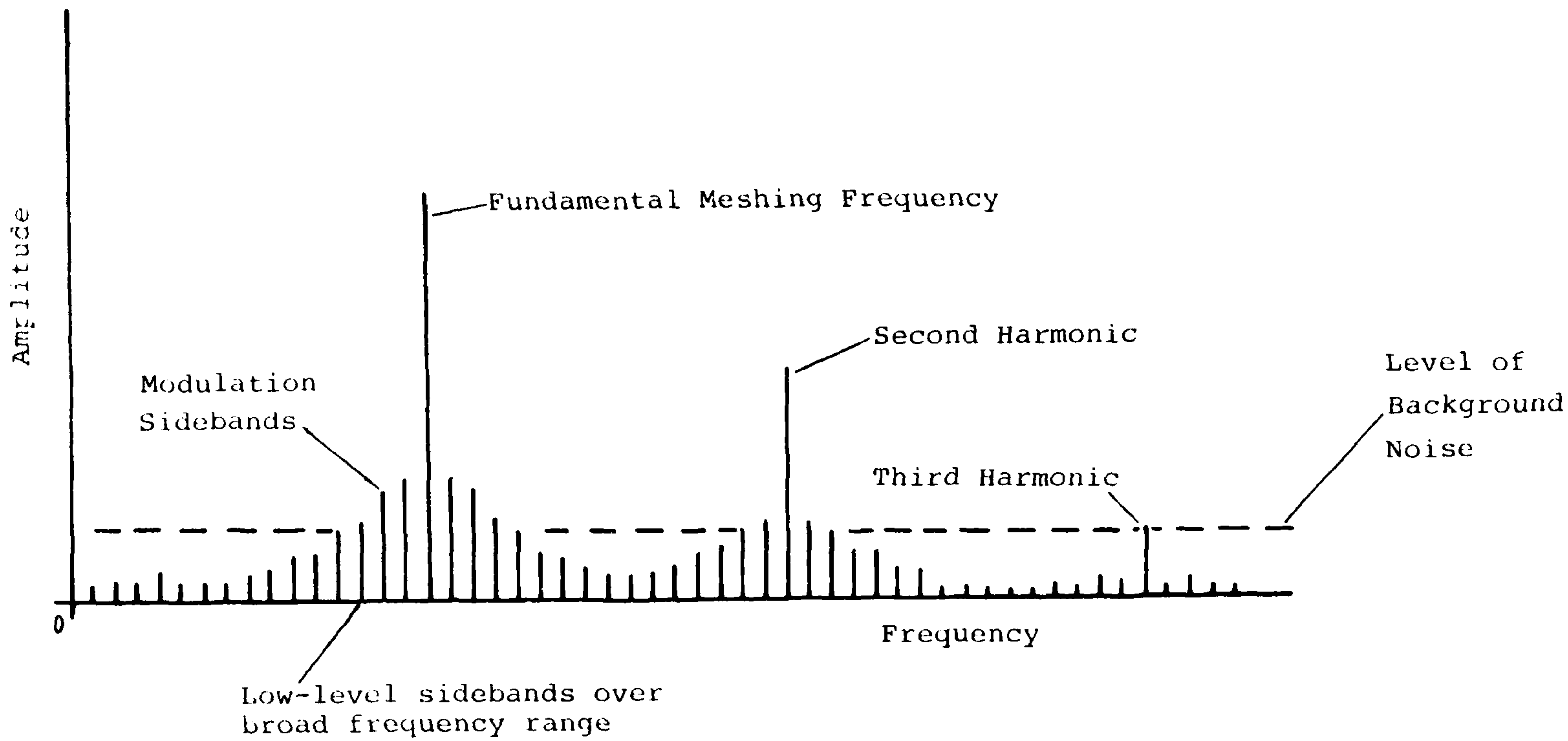

FIG. 1 SPECTRUM FOR A GEAR WITH A SMALL CRACK

Table 5 Suggested equipment purchases

Item	Description	Qty	Cost
1	Computer box 22 bit backplane with 8 quad slots Heavy duty power supply To suit DEC LSI11	1	1600
2	DEC LSI11/73 processor board	1	2500
3	Terminator/bootstrap/clock board	1	450
4	DLV11J quad serial I/O board	1	700
5	Analogue to digital converter board	1	1500
6	512 k byte memory board	1	2700
7	IEEE 488 interface board	1	700
8	RX02 disc drive Winchester disc drive Disc controller board	1	5700
9	DEC VT240 terminal	1	2800
10	Dot matrix serial printer	1	900
11	Wavetek 752A low-pass brickwall filter	1	8500
12	DEC RT11 operating system copy licence	1	750
13	IEEE 488 cable 1 metre	2	200
14	Phase-locked frequency multiplier (Supplied by ARL)	1	0
		Total	$29000

Notes

1. Prices valid at 29th August 1984

2. For full specifications of above items contact ARL

Table 4 Analyses using filtered vibration for speed signal

Box	Hours	Torque	Tape	K
WAK143	133.4	410	4/83	3.16
				3.47
				3.39
		300		3.26

Table 3 Analyses using alternator for speed signal

Box	Hours	Torque	Tape	K
WAK128	265.4	440	10/84	2.02
				1.93
WAK129	55.2	440	20/84	2.62
				2.67
WAK140	123.2	440	21/84	2.26
				2.43
WAK151	36.5	440	18/84	2.79
				2.84
		300		2.18
				2.07
WAK153	56.0	440	20/84	2.33
				2.53
WAK156	57.5	440	21/84	3.01
				3.24
WAL180	453.1	400	20/84	3.02
				2.90
				2.99
WAL185	105.8	440	10/84	2.27
				2.36
WAL242	386.4	400	19/84	2.79
				2.64
WAM284	5.6	400	17/84	2.53
				2.41
WAP470	95.4	400	15/84	2.79
				2.51
WAP477	447.9	440	14/84	2.46
				2.95

Table 1 Kurtosis during enhancement of the signal average

Signal	K
Original signal average	1.7
After band-pass filtering	1.6
After elimination of meshing	7.0
After enveloping	9.2

Table 2 Analyses using filtered vibration for speed signal

Box	Hours	Torque	Tape	K
WAK128	253.2	440	34/83	2.34
WAK152	530.3	400	34/83	2.14
WAL180	421.6	440	34/83	2.66
WAL187	645.5	400	34/83	2.39
		300		2.52
WAL189	212.3	300	29/83	2.55

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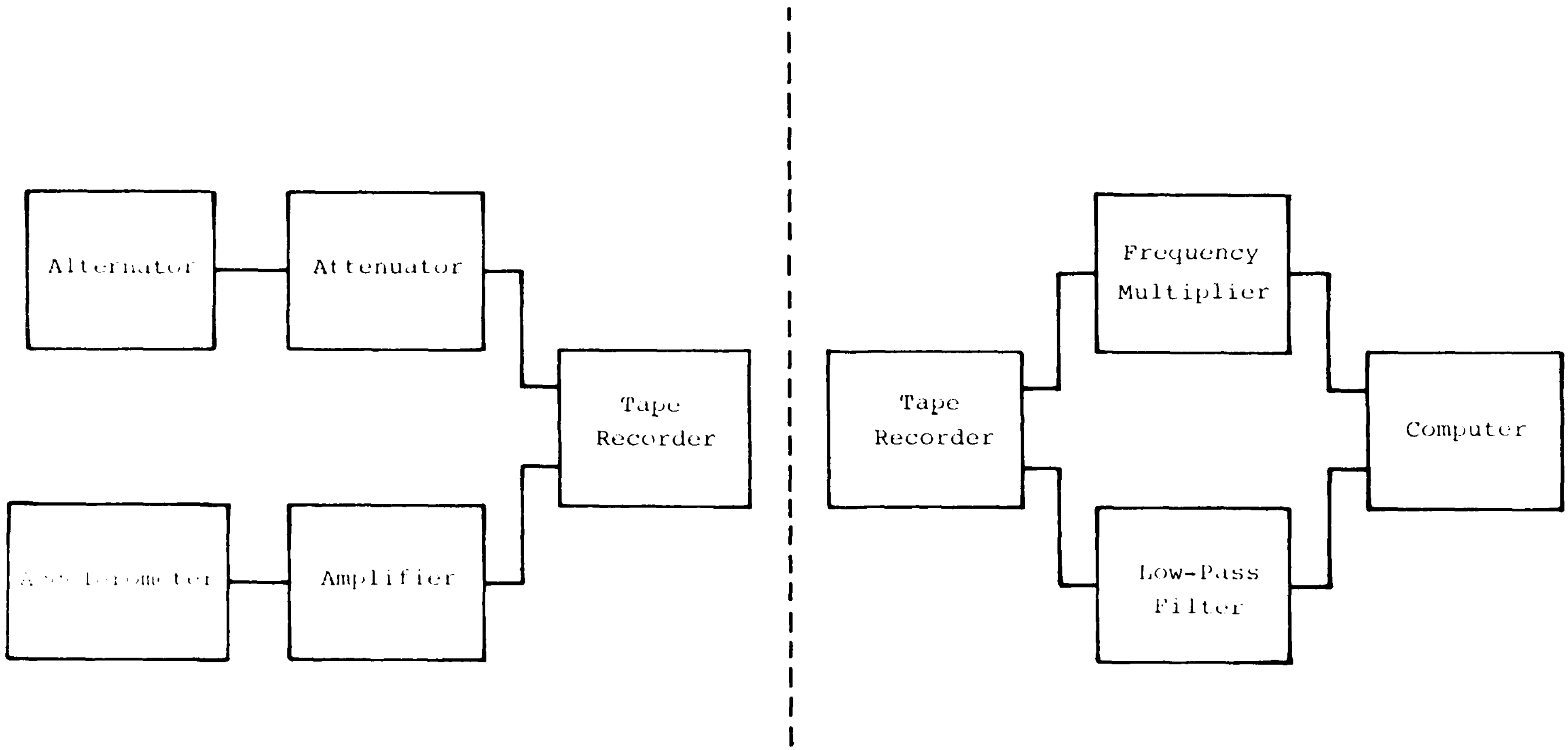
4. CONCLUSIONS

This technical memorandum has reviewed the recent developments which have been made at ARL in the signal averaging, enhancement and assessment of the vibration of the input bevel pinion in the Wessex helicopter main rotor gearbox. It has been demonstrated that these techniques make it possible to detect fatigue cracks of the type experienced in gearbox WAK143 earlier than 103 hours before failure.

Firm proposals have been given for the items of new equipment, estimated to cost $29000, which will be required if the present program of vibration monitoring is to be modified to take advantage of these developments. It is proposed that following further studies by ARL the new equipment will enable the same techniques to be applied to other major gears in both Wessex and Sea King with consequent improvements in the safety of operation of these aircraft.



(a) In Flight

(b) On Ground

FIG. 9 EQUIPMENT FOR RECORDING AND ANALYSIS OF VIBRATION

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1. a. AR No	1. b. Establishment No	2. Document Date	3. Task No
AR-003-985	ARL-AERO-PROP-TM-422	JANUARY 1985	DST82/051

4. Title	5. Security	6. No Pages
Proposal for modifications to the Wessex helicopter main rotor gearbox vibration monitoring program.	a. document: UNCLASSIFIED b. title: U c. abstract: U	7. No Refs: 15

8. Author(s)	9. Downgrading Instructions
P.D. McFADDEN	-

10. Corporate Author and Address	11. Authority (as appropriate) a.Sponsor b.Security c.Downgrading d.Approval
AERONAUTICAL RESEARCH LABORATORIES P.O. BOX 4331 MELBOURNE, VIC. 3001	-

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14. Descriptors		15. COSATI Group
Vibration Gearboxes Helicopters	Signal averaging Condition monitoring	01030 13090 14020

16. Abstract

Modifications to the RAN Recorded Tape Vibration Analysis Program for the condition monitoring of the main rotor gearbox in the Wessex helicopter are proposed to take advantage of recent developments in the techniques of signal averaging and computer enhancement of vibration data.

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16. Abstract (Contd)		
17. Imprint AERONAUTICAL RESEARCH LABORATORIES, MELBOURNE		
18. Document Series and Number Aero-Propulsion Technical Memorandum 422	19. Cost Code 41 7425	20. Type of Report and Period Covered
21. Computer Programs Used		
22. Establishment File Ref(s)		

END

FILMED

7-85

DTIC